

209945

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Report: Comprehensive System Models: Strategies for Evaluation

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General Considerations

The task of evaluating comprehensive earth system models is vast, involving validations of every model component at every scale of organization, as well as tests of all the individual linkages. Even the most detailed evaluation of each of the component processes and the individual links among them should not, however, engender confidence in the performance of the whole. The integrated earth system is so rich with complex feedback loops, often involving components of the atmosphere, oceans, biosphere, and cryosphere, that it is certain to exhibit emergent properties very difficult to predict from the perspective of a narrow focus on any individual component of the system. Therefore, a substantial share of the task of evaluating comprehensive earth system models must reside at the level of whole system evaluations.

Since complete, integrated atmosphere/ocean/biosphere/hydrology models are not yet operational, questions of evaluation must be addressed at the level of the kinds of earth system processes that the models should be competent to simulate, rather than at the level of specific performance criteria. Here, we have tried to identify examples of earth system processes that are difficult to simulate with existing models and that involve a rich enough suite of feedbacks that they are unlikely to be satisfactorily described by highly simplified or toy models. Our purpose is not to specify a checklist of evaluation criteria but to introduce characteristics of the earth system that may present useful opportunities for model testing and, of course, improvement.

The process of evaluating comprehensive earth system models will parallel, in many respects, the process of evaluating models of individual components of the system. For example, much can be learned about both comprehensive and component models as a result of intercomparisons of models from different groups, using standard data sets (e.g., Cess et al., 1989). Another need common to both kinds of models is assessments of stability and predictability, determined from long runs without external forcing. Both component and comprehensive models need to be evaluated on time scales ranging from very short (days or months) to very long (millennia or even longer). Finally, it is crucial to integrate the processes of model development, data gathering, and model testing, to insure that the data are relevant to testing the models.

The potential for enormous physical, economic, and social consequences of global climate change, and the critical role that comprehensive earth system models will play in future scientific and policy decisions, place unusual requirements on the way validations are conducted and on the translation of model validations into assessments of confidence (Houghton et al., 1990; MacCracken et al., 1990). Here, we have not focused on issues related to assessing model accuracy and expressing those assessments to the scientific and nonscientific communities; rather, we have attempted to identify kinds of tests that facilitate broad communication in this interdisciplinary endeavor and that encourage scientific extensions and improvements in the models.

Experiments at a Range of Time Scales

One of the central complications in earth system modeling is the functional importance, for the entire earth system, of interactions among processes operating over a broad range of time scales. Much of the task of evaluating comprehensive system models must, therefore, involve the fidelity with which component processes interact to simulate realistic amplitudes and dynamics of the behavior of earth system components as well as the coupled system, over the entire range of functionally important time scales. At each time scale, earth system processes may reflect different contributions from each of their component processes; for example, a component that is relatively insignificant over the short term may be quite important over a long time scale. Therefore, analysis of whole system responses at a range of time scales may provide insight into which model components need improvement. Experiments on a range of time scales, in combination with sensitivity analyses (studies of the results of changes in the model's initial conditions or internal parameters), establish a frame-

work for assessing the quantitative role of individual component processes in earth system responses. As we discuss below, there are critical unknowns at every time scale. A focus on these unknowns will insure that model evaluation produces a sensible distribution of emphasis among the components of the comprehensive model.

The Diurnal to Annual Time Scale

Even on a time scale of hours or days, the behavior of coupled and component models may be dramatically different. One clear example of this is the difference in climate predicted by atmospheric general circulation models (GCMs) with and without mechanistic descriptions of the biosphere (Dickinson and Henderson-Sellers, 1988; Shukla et al., 1990). Another motivation for emphasizing the short end of the time scale concerns the relative ease of gathering high-quality data over short intervals.

Clouds, Radiation, and Convection

Cloud feedback is a quantitatively dominant component of existing global change scenarios. The direct radiative effect of a doubling of atmospheric CO_2 is predicted to increase global net radiation by approximately 2 W/m^2 , a change likely to be amplified approximately twofold as a result of the effects of increased temperature on atmospheric moisture (Hansen et al., 1984). Increased convection due to climatic warming could, however, dry the upper and middle troposphere, although experimental evidence indicates approximately the predicted water-vapor feedback (Ravel and Ramanathan, 1989; Rind et al., 1991). Increased cloudiness caused by increased atmospheric moisture has large and uncertain effects on the water vapor amplification. In a comparison of 14 GCMs, climate sensitivity to a perturbation in sea surface temperature (SST) varied approximately threefold, primarily as a result of differences in cloud feedbacks (Cess et al., 1989).

Several issues in the general area of cloud feedbacks pose unambiguous, but relatively easily tested, challenges to the explanatory power of earth system models. Satellite data from the International Satellite Cloud Climatology Program, the Earth Radiation Budget Experiment (ERBE), and microwave sensors provide a rich data base for comparison with GCM cloud climatologies. At the daily to annual time scale, many of the cloud questions are most relevant to atmospheric GCMs, but at longer time scales they involve all components of the earth system. A primary challenge for global models should be to accurately reproduce the diurnal cycle of cloudiness and cloud effects on surface energy balance. At present, the GCMs do not do

this well, partly because they do not incorporate realistic cloud properties, as measured from satellite data, and partly for reasons not yet understood. One example of a property poorly represented in the existing GCMs is the cloud albedo, which clearly is as high as 90–95% (Ramanathan, personal communication) for thick clouds with tops above the bulk of the atmospheric water vapor, but is constrained to lower values in current GCMs.

Another poorly understood but potentially important cloud feedback involves the upper limit of 305 K on sea surface temperature in the Western equatorial Pacific. This robust cap, which is unexpected from simple energy balance considerations (Ramanathan, personal communication), appears to result from the linkages between warm SSTs, deep convection, and the formation of large, highly reflective cirrus anvils (Ramanathan and Collins, 1991). The high albedo of these cirrus anvils makes them act as thermostats with the potential to provide a strong negative feedback on global warming.

Other important unresolved questions concern the origin of clouds. To the extent that oceanic cloud formation is limited by the availability of condensation nuclei, biotic controls on dimethyl sulfide (DMS) emissions and the atmospheric sulfur cycle assume critical roles in the regulation of cloudiness (Charlson et al., 1987). Differences in cloud albedo resulting from differences in condensation nuclei potentially complicate the situation even further and further augment the biospheric and chemical controls on cloudiness. Another unexplained aspect of the control of cloudiness concerns a feedback involving storm tracks. If clouds are responsible for much of the equator-to-pole temperature gradient and if this temperature gradient drives the storm tracks, then do clouds and the storm track constitute a self-reinforcing stable interaction? A spectral analysis of the dynamics of cloudiness could go a long way toward answering this question. If the storm track is a major determinant of cloudiness, then the power maximum in the spectral analysis should approximate the two- to six-day period of the storm track.

Effects of anthropogenic sulfur emissions on clear sky aerosols and on cloudiness may also be critical. Radiative effects of increased aerosols are poorly known, but the role of sulfur chemistry in climate regulation has been emphasized by recent suggestions that the net warming from CO₂ has been largely offset by a net cooling from increased cloudiness (Wigley, 1989; Wigley, 1991) resulting from anthropogenic S emissions.

Oceans

A fully interactive ocean is a critical driver of atmospheric processes, but it also responds to forcing from the atmosphere and

cryosphere (Rintoul report, this volume). Coupling among the oceans, atmosphere, and cryosphere generates ocean signatures that can serve as indices for evaluating coupled models. Because essentially all ocean processes are sensitive to these interactions, a broad suite of processes has potential application in testing and developing coupled models. The mixed layer is especially sensitive to interactions with the atmosphere and cryosphere, and its spatial and temporal structure clearly merits focus. In addition, a coupled model should be able to reproduce observed patterns of temperature and salinity, as well as currents.

Chemistry/Tracers

The coupling of chemistry (including sources) with large-scale circulation, convection, clouds, and solar radiation generates the observed variations ("chemical signatures") in a large variety of chemical trace species in the lower atmosphere.

Seasonal cycles in large-scale transport and chemistry interact with the source distribution to produce chemical climatologies (e.g., mean concentration as a function of latitude, altitude, and season) that are unique signatures for each species. For tropospherically inert species (the chlorofluorocarbons, CO_2 , krypton-85) the resulting signature is strictly a function of sources and transport. For some species there are limited chemical removal mechanisms ($\text{OH} + \text{CH}_4$, $\text{OH} + \text{CH}_3\text{CCl}_3$) or physical processes (as for water vapor) that control the seasonal cycles. For other more reactive species (carbon monoxide, oxides of nitrogen, ozone) we must include in situ sources that are chemically dependent on a suite of other species or sources (nonmethane hydrocarbons, urban air pollution, lightning-generated nitric oxide). For these latter gases, the resulting chemical climatologies are difficult to predict and verify with current models.

Chemistry interacts with the boundary layer on a diurnal cycle, and the combination of chemistry and mixing determines the net flux of some key species from the surface of the earth to the free troposphere. Less reactive species with calibrated local or regional sources (CFCs, radon, methane, and possibly water vapor) provide measures of the diurnal venting of the boundary layer, and their vertical profiles measure the extent of convective transports. More reactive species (DMS, isoprene) are destroyed rapidly in the boundary layer by reaction with the hydroxyl radical (OH) or ozone (O_3) and thus have distributions that represent a balance between surface emissions, chemical loss and mixing. Other reactive species (O_3 , oxides of nitrogen, OH) are involved in very complex chemical cycles in the boundary layer. In particular, ozone loss by deposition to vegetation is an important component of the global ozone budget

and will be regulated not only by mixing of ozone into the boundary layer, but also by the coupled photochemistry within.

Hydrologic Cycle

Success in modeling the evaporation/precipitation balance depends, at the first order, on the integrated behavior of an atmospheric GCM, a surface hydrology model for estimating runoff and soil moisture, and a biosphere model, which influences albedo, aerodynamic roughness, and the surface conductance to water vapor. The hydrologic cycle provides both short- and long-term as well as small- and large-area opportunities for evaluating integrated atmosphere/biosphere/hydrology models.

At the small-area extreme, a comprehensive model should duplicate natural precipitation regimes, for both the detailed statistics of frequency and distribution and the monthly and annual totals. The current generation of atmospheric GCMs used for climate research provides precipitation sums that can be compared with measurements, but the extreme spatial and temporal variability of surface precipitation records, in combination with the GCMs' large grid cells and limited description of surface topography, brings into question the utility of any model evaluation of precipitation sums, especially for less than monthly intervals. On the other hand, as comprehensive models incorporate improved descriptions of the biosphere and of surface hydrology, detailed statistics of precipitation frequency and distribution should provide a basis for increasingly informative evaluations.

For larger regions, the spatial and temporal variability of precipitation combines with the patchy distribution of precipitation recording stations to limit the utility of model evaluations based on precipitation records. While not offering precipitation and evaporation as separate quantities, runoff in major river basins provides a powerful check on regional hydrologic balances. River basin runoff is useful not only because it integrates over large areas, but also because it integrates over the atmospheric, biospheric, and hydrological components of a comprehensive model.

Biosphere

Several lines of evidence indicate that relatively simple spectral indices derived from satellite-based multispectral sensors, for example, the normalized difference vegetation index (NDVI), when appropriately screened, provide reasonably accurate measures of net primary production, especially when integrated over an entire season (Tucker et al., 1986; Fung et al., 1987; Sellers, 1985). NDVI and other simple spectral indices clearly offer room for improvement, but their current performance and global coverage is sufficient to justify

their use as checks for a comprehensive earth system model. Specifically, an integrated model containing an internally driven biosphere component should generate a quantity and phenology (seasonality) of ecosystem production that can be checked against satellite data.

Biosphere function can also be checked against its chemical signature in the atmosphere. These tests require not only that the biosphere component be accurate and accurately driven from other models but also that atmospheric tracer and chemistry modules accurately distribute and process the chemical signatures. Useful targets for analysis include the latitude-dependent annual cycle of atmospheric CO₂ concentration (Fung et al., 1987), the pole-to-pole gradient in mean annual CO₂ (Tans et al., 1990), and the isotopic composition of atmospheric CO₂ (Keeling et al., 1989). Parallel analyses with other trace gases, especially methane and nitrous oxide, will be very useful. The power of atmospheric probes for biosphere function will increase as the frequency and spatial density of high-accuracy sampling, especially over land areas, increases (Tans, in press).

Primary Land Sites

A comprehensive earth system model should, ideally, model all portions of the earth's surface with uniformly high accuracy. In one sense, data from all sites should be equally useful for model evaluation. Areas differ, however, in several respects that influence their ability to contribute interpretive power. Important sources of this variation include (1) the prominence of climatic features that are difficult to predict with single-component models and that have major effects on the coupled earth system, and (2) historical impacts of anthropogenic forcing with important feedbacks on climate. Five regions that clearly express one or both characteristics are discussed below.

Arctic

Arctic regions should be a focus of emphasis in the development and evaluation of comprehensive models because several features of the Arctic atmosphere, oceans, and land surface, although they are difficult to predict with single-component models, have potentially major feedbacks on climate. In the atmosphere, the abundance and radiative consequences of stratus clouds present a major difficulty for existing atmospheric GCMs. These problems are due, at least partly, to the role of Arctic cloudiness in a powerful positive feedback loop. Arctic cloudiness is a major driver in the equator-to-pole gradient in solar radiation absorption at the surface, and this gradient is critical for the storm track. To the extent that the storm track is responsible for Arctic clouds, the cloudiness is self-reinforcing (see "Clouds, Radiation, and Convection," above).

Potential climatic effects of the extent, duration, and thickness of Arctic sea ice make the atmosphere/ocean interface particularly critical in the Arctic. Consequences of changes in sea ice for albedo cannot be accurately determined until cloudiness is better known. Similarly, the albedo of sea ice is critically dependent on the extent of snow cover over the ice, which depends on the extent to which heat flux into the atmosphere resulting from freezing at the ice-ocean interface generates low clouds and snow. Other important but poorly known aspects of the ocean/atmosphere interface include the role of the spatial separation of ice formation and melting in transporting heat to the pole (see Hibler, this volume) and the role of salinity stratification in limiting poleward heat transport by preventing thermal overturning.

Several aspects of the Arctic land surface also have potentially major effects on climate. Changes in albedo resulting from changes in the extent and duration of snow cover are one critical area, but, here again, interactions with cloudiness will dominate the magnitude of the consequences. Changes in the distribution of permafrost and in the active (thaw) depth of permafrost regions may have major impacts on carbon storage in the biosphere. In addition, decreased permafrost may dramatically affect the atmospheric methane (CH_4) budget, as a consequence of the release of methane hydrates currently stored in permafrost.

India

The Indian subcontinent should be a focus for intensive studies because understanding the formation and continental penetration of monsoons will require an effort integrating atmosphere, ocean, and land models. Specific factors that need to be understood include the extent to which warming in the western equatorial Pacific sea surface can prevent monsoon formation, the role of terrestrial vegetation in modulating the land surface energy balance, and the subsequent effects of such modulation on the regional atmospheric circulation.

Africa

Africa, especially northern Africa, provides excellent opportunities for comprehensive model evaluation for at least two reasons. First, the sensitivity of climate to the characteristics and seasonal movement of the intertropical convergence zone (ITCZ) is clearly documented, meaning that accurate climate prediction for the region must build from a solid understanding of the dynamics of the ITCZ. Second, biomass burning in Africa, as well as in other regions, has major impacts on the chemistry of the atmosphere.

U.S. Midwest

The midcontinental United States offers other opportunities to evaluate our understanding of the controls on continental climates because the climate in this region is so sensitive to the interaction of the storm track and pressure belts. In addition, the U.S. data base on agricultural production and consumption of irrigation water, as well as the detailed process information available for the function of many ecosystems, provides an unmatched resource for evaluating predictive models of biosphere function.

Amazon

One final region that should be an intensive focus for evaluation of comprehensive models is the Amazon basin. Weather in this region is to a significant degree internally generated and appears to be quite sensitive to the status of the vegetation (Dickinson and Henderson-Sellers, 1988), a characteristic that also has consequences for the convergence of moisture from outside the region (Shukla et al., 1990). Rapid deforestation in the Amazon is providing a test of the consequences of vegetation change.

Need for Increased Process-Level Data

The primary focus of this chapter is on opportunities for evaluating comprehensive earth system models. At the diurnal to annual time scale, taking advantage of many of the opportunities will require more than comparisons between existing data sets and results of new models or newly integrated models. For many components of the coupled earth system, the shortage of process-level data is at least as great as the need for improved models. Specific data needs include (1) continuing studies of the earth's radiation budget, with measurements analogous to those of the now-completed ERBE; (2) detailed studies of Arctic sea ice dynamics, possibly using microwave data; and (3) improved land surface hydrology, emphasizing landscape-scale evapotranspiration and major basin runoff.

The Annual to Decadal Time Scale

At the annual to decadal time scale, many of the most important unknowns concern the nature and dynamics of the feedbacks, especially feedbacks among the atmosphere, oceans, and land, that regulate major climatic features. Here, we identify six kinds of processes (i.e., El Niño–Southern Oscillation events, extreme climate events, sea ice, oceanic conveyor belt, trace gases, and volcanoes) with potentially dramatic but incompletely understood origins and/or ramifications for climate.

ENSO

The first hypothesis that the atmosphere and oceans interact as a coupled system to control climate at interannual time scales (Bjerknes, 1966) emerged from analysis of what was then called the Southern Oscillation and is now referred to as El Niño–Southern Oscillation. ENSO events, characterized by a strong increase in the eastern equatorial Pacific SST and a strong decrease in upwelling in this region, are incompletely understood but clearly involve atmospheric and oceanic components. ENSO events appear to be initiated by changes in the tropical atmospheric circulation, which lead to changes in the ocean circulation and the eastern Pacific SSTs, which lead, in turn, to large changes in the distribution of precipitation (Philander, 1990).

ENSO events in 1972 and 1976 were preceded by periods of several months of unusually strong southeasterly trade winds, leading to the hypothesis that ENSO is primarily an ocean response to changes in wind shear, the “Kelvin wave hypothesis.” The 1982–83 episode, the strongest in this century, was, however, completely different (Rasmusson and Wallace, 1983), leaving the basic mechanism in doubt. Both because the events clearly involve atmospheric and oceanic components and because they have dramatic effects on climate, ENSO generation and dynamics provide an excellent opportunity for evaluating coupled earth system models. The primary test, focusing on the frequency and spatial and temporal structure of the events, will involve only atmospheric and ocean dynamic models, but the suite of component models should be expanded to include a biosphere model, to evaluate changes in abundance and frequency of organisms resulting from changes in SST and upwelling. Chemical models will be necessary to assess changes in CO₂ and CH₄ signatures resulting from changes in the distribution of sources and sinks (biotic and abiotic) as well as changes in atmosphere and ocean transport.

One useful strategy for exploring ENSO events is likely to involve coupled model runs without external forcing. Examining the dynamics of and interactions among SST, surface pressure, winds, convection, and radiation should provide a basis for testing mechanistic hypotheses as well as for comparing natural and model dynamics. For the latter objective, it will be important to focus on the temporal distribution of the inherent variability in the coupled model.

Extreme Events

Extreme events, for example, the North American drought of 1988, provide excellent opportunities for testing the competence of coupled models. Useful information should come both from tests

designed to duplicate a particular episode and from characterizations of the statistical structure of related events in runs without external forcing.

The 1988 North American drought is unusually interesting because, like ENSO, it was probably initiated by changes in winds, which altered SSTs, which then altered atmospheric circulation and the distribution of precipitation in regions far removed from the area of initial atmosphere-ocean interaction (Trenberth et al., 1988). For this and similar well-characterized extreme events, the standards for accurate simulation with a coupled model can be stated very precisely, making them excellent validation exercises.

In general, we need more information on the inherent variability of the climate predicted by coupled models. Comparisons between the distributions of natural and of model variability will provide useful information about the mechanisms driving real climate variation.

Sea Ice

Natural fluctuations in the extent and duration of sea ice are incompletely known but are critical for evaluating the performance of a coupled earth system model. High-latitude cloudiness makes it difficult to assess ice with visible and thermal satellite sensors, but microwave sensors can provide a clear picture of ice extent, though not thickness. Since ice extent is influenced by atmospheric and ocean processes, temporal patterns of ice extent, with and without cloudiness, will be useful for evaluating coupled ice/ocean/atmosphere models.

Sea ice plays a potentially critical role as an amplifier of global warming. Since the albedo of open water is less than that of ice and much less than that of snow-covered ice, any loss of sea ice extent or duration should result in further warming, promoting a positive feedback effect. This simple scenario fails, however, to account for several critical aspects of the polar, and especially the Arctic, climate. An accurate model of the role of sea ice in climate regulation will probably need to address (1) ice/cloudiness interactions, (2) the role of ice movement in heat transport, (3) the regulation of lead (open water) area in sea ice regions, and (4) the role of fresh meltwater in limiting the cooling and subsequent overturning of saline surface waters.

Conveyor Belt

As warm surface waters move into the North Atlantic, they cool by approximately 8°C, releasing a quantity of heat equal to about 30% of the solar radiation incident on this region (Broecker and Denton, 1989). This heat input warms the region, increasing ocean evapora-

tion and, consequently, increasing the salinity of the North Atlantic. Once these saline waters cool sufficiently, they sink to the ocean bottom and move equatorward, driving a massive conveyor belt that transports heat into the North Atlantic. Some evidence points to interannual and decadal-scale fluctuations of salinity, convection, and deep water formation in the northern North Atlantic. The maintenance of the conveyor belt depends on ocean/atmosphere/ice interactions, so that its operation needs to be explored with coupled models. The conveyor belt appears to be maintained by a positive feedback cycle in which the northward movement of warmer surface waters is critical to support enough evaporation to increase salinity to a level sufficient to sink the surface waters to the deep ocean. Externally forced runs with coupled models will provide excellent opportunities for characterizing the range of conditions over which the conveyor belt operates.

Trace Gas Signatures

On the annual to decadal time scale, the chemical constitution of the atmosphere can be substantially changed by anthropogenic emissions, changes in biosphere and ocean exchanges, and volcanic activity. In addition, changes in the atmospheric temperature, circulation, and composition can alter the fate and dynamics of trace species (Prinn and Hartley, this volume). The accuracy of any model designed to predict the concentration and distribution of any trace gas is critically dependent on the atmospheric circulation and on the intensity and distribution of sources and sinks. Assessments for different trace species will require simulations with models incorporating different numbers of components. For relatively inert tracers like CFCs and krypton-85, atmospheric GCM wind fields and descriptions of anthropogenic sources should suffice. Predictions of CO₂ will require a biosphere component for specifying sources and sinks as well as an ocean component for specifying air-sea exchanges. Chemically reactive species like CH₄, nitrous oxide (N₂O), and DMS will demand the integration of an interactive chemistry module.

Studies of trace gas signatures will be especially useful in model runs exploring other sources of variation. For example, ENSO events, volcanos, and the 11-year solar cycle are all associated with substantial changes in atmospheric chemistry.

Volcanos

Major volcanic eruptions have large impacts on the radiation balance and chemistry of the atmosphere. Thus, coupled model runs simulating real eruptions provide a powerful probe for evaluating model responses to short-term, high-intensity external forcing. In

the realm of atmosphere-ocean dynamics, one critical parameter to study is the time until maximum cooling. The spatial structure of the plume can serve as a tracer for an atmospheric GCM. Interactions between upper-atmosphere dynamics and stratospheric chlorine/ozone chemistry will provide useful tests for coupled atmospheric chemistry/dynamics models.

Coupled model runs including emissions from biomass burning and urban air pollution should provide useful comparisons with volcano simulations. These anthropogenic sources of external forcing will differ from volcanic forcing in continuity, spatial distribution, chemical constitution, and elevation of injection.

The Last Century

The period from approximately 1920 to the present offers a unique set of opportunities for evaluating coupled models. The primary advantage of models simulating the 20th century, as opposed to some other century, is the availability of high-quality climate data. Two kinds of additional considerations, however, motivate an emphasis on a period of several decades. First, observational records document significant climate variability within this time period. Records from meteorological stations, when combined to estimate global trends, indicate strong warming in the early 1920s, followed by nearly a decade of cooling during the 1940s. Global mean temperatures through the 1950s and 1960s were relatively stable, while the 1970s was a period of strong warming, with five-year mean global temperature about 0.6°C warmer in 1980 than in 1910 (Folland et al., 1990; Ghil and Vautard, 1991). These decades were not a period of high volcanic activity, and the eruptions that did occur were reasonably well characterized. Variations in greenhouse gases are also well known, though variations in solar forcing and anthropogenic aerosol forcing (the latter probably increasing in amount, resulting in net cooling) are not. Second, long runs of atmospheric GCMs without external forcing demonstrate inherent climate variation over a range of time scales, from a year to a century or more (Hansen et al., 1990).

Given the evidence for variability in nature as well as in atmospheric models, it is interesting to ask how the variation is modulated in coupled models of increasing complexity, with and without external forcing. A sequence of simulations beginning with atmospheric simulations without external forcing is computationally realistic as well as intellectually heuristic. For example, a comparison of models with and without fully interactive oceans will address the role of fully interactive oceans in decadal-scale climate variation. In

addition, the record of ocean heat flux imbalances in a model without a fully interactive ocean should provide a basis for understanding the differences. Adding historical forcing from greenhouse gases and, for the most recent solar cycle, solar variation will begin to address the question of how external forcing impacts the inherent variability of the climate system. With an interactive biosphere model, the coupled model should be able to generate some of the changes in greenhouse gases internally, with only the anthropogenic components applied as external forcing.

The Last Millennium

The motivation for experiments involving the last millennium is an extension of the motivation for the hundred-year time scale. As we move further back in time, the quality of the climate record deteriorates, but a range of interesting new challenges for a coupled model emerges. While climate records for the last millennium hardly compare with those for the last few decades, a combination of several sources of information can lead to high-quality reconstructions. Useful sources of climatic information include descriptions in literature, records of the extent of mountain glaciers, pollen, tree rings, coral, high-resolution sediment cores, and ^{13}C . Long records of solar diameter may give some insight into variation in the solar output, and notations concerning the aurora provide an index of sunspot activity. Based on these sources of information, periods that emerge as candidates to challenge coupled models are the Little Ice Age, from about 1600 to about 1900, and the "Medieval Warm Period" several centuries earlier.

Climate changes during these periods were substantial. The current estimate is that, during the Little Ice Age, global mean temperature decreased by $1\text{--}2^\circ\text{C}$ and the cooling was global in extent, though probably confined to the winter. The Medieval Warm Period was probably less dramatic, in terms of both magnitude and areal extent (COHMAP Members, 1988). The basic question to address with studies of coupled models is whether inherent variations in the coupled earth system are sufficient to generate climate changes of this magnitude or whether they must be forced externally by solar and orbital factors or by changes in volcanism. There is some evidence for external forcing. Sunspot activity reached a minimum during the Little Ice Age (Eddy, 1976), and volcanic activity may have increased. New evidence indicates orbit-driven changes in the intensity of seasons, with periods ranging from 12 to 800 years. Yet, it is not known whether these forcings were sufficient to generate the climate changes. Neither is it known whether inherent variation is suf-

ficient. Inherent factors that might become significant at the millenium time scale include changes in atmospheric dust, driven by changes in precipitation and vegetation, and long cycles in the Atlantic conveyor belt.

The Paleo Time Scale

Moving further back in time, the level of detail in the data continues to diminish, but the magnitude of the climate changes continues to increase. Past climates and climate forcings over the era of ice ages, approximately the last 2.5 million years, are now the focus of several active modeling groups and are well enough known that standardized data sets should be developed and widely applied. Accurate simulation of at least one glacial/interglacial cycle, including the global distribution of climate change, nonlinear effects of ice development, and changes in the trace gas composition of the atmosphere, will be a critical test for a coupled earth system model.

For experiments concerning climate changes of the last five million years, the emphasis in model development and evaluation shifts from inherent variability without external forcing to model responses to external forcing. Forcing factors that need to be studied in detail include Milankovitch orbital variations (Kutzbach and Gallimore, 1988; Rind et al., 1989; Berger et al., 1990), changes in solar output (Foukal and Lean, 1990), changes in ocean barriers, and consequences of mountain building (Raymo et al., 1988; Ruddiman and Kutzbach, 1989). Feedbacks that are likely to become important with these external forcings include the role of ice sheets, the role of dust and glacial age aerosol, the role of CO₂ in amplifying radiation effects of orbital variations, and changes in the Atlantic conveyor belt. As in the present-day climate, amplification of external forcing by changes in atmospheric water vapor will be critical. Solid earth processes should be included in coupled models simulating long time scales because of such effects as crustal deformation resulting from ice accumulation.

The Last 125,000 Years

The past 125,000 years provide excellent opportunities for modeling earth system behavior because the system went through a large (interglacial-glacial-interglacial), well-documented variation and because the seasonal and latitudinally varying solar radiation changes that appear to have initiated and paced these large earth system changes are known exactly. These changes are due to changes in the season of perihelion (period of about 22,000 years) and in the tilt of the rotation axis (period of about 41,000 years).

Within the past 125,000 years there are opportunities to study three extreme states (6000, 18,000, and 125,000 years ago), the entire time evolution (125,000 years ago to present), and embedded large and abrupt oscillations (such as occurred at 11–10,000 years ago).

Extreme States

The most recent interglacial maximum, at 6000 years B.P., was a time when the Arctic was warmer and sea ice cover was reduced, when northern continental interiors were drier, and when northern monsoons were stronger. Several modeling groups have already shown that seasonal and latitudinal solar radiation changes on the order of 10 W/m^2 (due to orbital changes which placed perihelion in the northern summer and increased the axial tilt), when inserted in climate models, simulate these changes to some extent.

The most recent glacial maximum, at 18,000 years B.P., provides a contrasting example of the earth system in a glacial state with large ice sheets over North America and Europe, changed biomes, reduced atmospheric CO_2 , and changed ocean circulation, including stoppage of the North Atlantic conveyor belt. Most large modeling groups have already attempted to simulate these conditions with atmospheric models and are now beginning to work with coupled models.

The previous interglacial maximum, which occurred at 125,000 years B.P., had a climate somewhat similar to that of 6000 years B.P., but the insolation changes due to orbital changes were larger and the climatic changes mentioned above were even more extreme. Atmospheric CO_2 was at a relative (preindustrial) maximum. There is some evidence that the Greenland ice sheet was significantly smaller than present.

Evolution

A new opportunity is to try to model the time evolution of the earth system, starting 125,000 years B.P. and continuing to the present. This problem has already been studied with toy models and with rather detailed latitudinally varying models that include ice sheet, atmospheric, and ocean components. The possibility now exists to use more fully coupled three dimensional models (with an asynchronous coupling scheme for ice sheets, etc.).

Abrupt Changes

The earth system experienced several abrupt and large changes of several centuries' duration that are embedded within the more slowly evolving conditions mentioned above. The most recent ex-

ample was the period between 11,000 and 10,000 years ago, when the climate cooled and then warmed again abruptly. There is evidence that atmospheric CO₂ also changed abruptly and that the North Atlantic Ocean conveyor belt may have stopped and then restarted, possibly as a result of a massive influx of fresh water from melting glaciers into the North Atlantic. Several modeling groups are studying these phenomena (e.g., Rind et al., 1986).

Additional Model Studies

In addition to modeling the coupled atmosphere, ocean, ice, and biome changes at the above-mentioned times, there are opportunities for special studies. Oxygen and hydrogen isotopes, carbon isotopes, and dust distributions are known to vary significantly between glacial and interglacials, and there are opportunities to use tracer and source/link models to study these changes. In addition to CO₂ variations, mentioned earlier, CH₄ varied significantly and at the same period as the changes in season of perihelion (about 20,000 years).

System feedbacks, such as water vapor (greenhouse) feedback and snow/sea ice feedback, can potentially be studied over a range of extreme climatic states that may help us understand better the cause of apparent temperature stability in the tropics and the nature of high-latitude feedbacks at times of apparent significant reduction in sea ice. The large swing in atmospheric CO₂ concentration between 270 ppm (interglacial) and 200 ppm (glacial), documented in the Vostok ice core, presents a special opportunity to simulate the changes in the carbon cycle that must have occurred.

2-5 Million Years Ago

The marked glacial-interglacial fluctuations described above for the past 125,000 years began to be evident around 2.5 million years ago. Prior to that time, the earth probably had a climate significantly warmer than at present. In contrast to the glacial-interglacial changes, which are believed to be caused by orbitally produced changes in seasonal and latitudinal distributions of solar radiation, the fundamental causes of the general, long-term evolution from warmer to cooler climate are not known.

The role of plate tectonics in changing land-ocean distributions, while of fundamental importance for understanding early earth climates on the scale of tens to hundreds of millions of years ago, is not likely to have been a large factor in the past several million years. However, tectonic forcing could have been important in other ways. One factor may have been the important changes in ocean circulation produced by changing ocean "gateways." The closing of the

Isthmus of Panama several million years ago may have significantly altered the ocean circulation. Another factor may have been the uplift of mountains and plateaus. The associated carbon cycle changes related to changes in weathering caused by uplift may have produced a downward trend of atmospheric CO₂ concentrations that partially explains the cooling trend. However, the details are very poorly known, as are the CO₂ levels. Modeling studies of these possibilities are beginning.

In contrast to the last 125,000 years, many fewer data are available for comparison with model results for these earlier times. Nevertheless, the earth system was so different at these times that even relatively poor data sets reveal some of the large differences from the present.

The most important reason for giving some attention to this period is that it represents the most recent time when climate was significantly warmer than during recent interglacials. Increased levels of atmospheric CO₂ may have been partially responsible for the warmer conditions. Some aspects of system behavior under these extreme conditions are therefore of interest in order to check feedback sensitivities under extreme warm conditions (open Arctic, etc.).

Model Perturbations and Future Simulations

Thus far, we have emphasized opportunities for evaluating coupled models by comparison with observations. Two other classes of experiments have great potential to advance our understanding of the coupled earth system. These are long runs without external forcing to assess climate predictability and runs with large forcing to evaluate climate responses to major perturbations. Determining the limits to climate stability should be a critical objective of both kinds of experiments.

Climate predictability is a much discussed but poorly understood topic. Small changes in initial conditions clearly lead to different climate trajectories. The differences appear to be subtle over short time periods (Hansen et al., 1990), but do they ever increase with time? Daily weather records provide a short-term perspective on the limits to the predictability of climate, but very little is known about the long term and about whether coupling of modules tends to suppress or amplify the variability inherent in individual modules.

Experiments with major perturbations have two objectives. One is to explore the responses of the coupled earth system to hypothetical but potentially realistic external forcings. The other is to explore the kinds of conditions under which the climate becomes unstable and switches between fundamentally different states. Under the first

objective, interesting experiments would include coupled model runs with CO₂ elevated to three or four times present. This would extend the CO₂ story to something approaching a possible equilibrium, in addition to exploring responses to a major perturbation. Simulations of major volcanic eruptions and of perturbations like permafrost and polar ice sheet removal would similarly probe extremes.

Watson and Lovelock's (1983) Daisyworld is a toy model that illustrates the concept of limits to climate stability. With the real earth system, climate stability is unknown. The fact that ice sheets have advanced and retreated many times argues for substantial stability, but the climate may function in wells of potential energy that separate contrasting states. Changes in flower color can only do so much to maintain temperature in Daisyworld. In the real earth system, where are the limits to, for example, the thermostat function of clouds? Or, as emissions of reactive atmospheric species continue to increase, will they eventually so completely deplete the atmosphere of OH⁻ that it no longer plays a significant role in removing these species? These and similar questions clearly involve multiple components of the coupled earth system and must be explored with fully interactive models.

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